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SOFT-START OF DC LINK CAPACITORS FOR POWER ELECTRONICS AND DRIVE SYSTEMS

RELATED APPLICATION

[0001] This application claims priority under 35 U.S.C. §119(e) of U.S. Provisional Application No. 60/326,191 filed on October 2, 2001, the entire contents of which are herein incorporated by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to a soft-start system in an electrical power system and in particular to the soft-start of DC links for capacitor banks of aerospace/industrial power electronics and drive systems.

BACKGROUND OF THE INVENTION

[0003] Soft-start systems are used in power conversion and distribution systems to limit the in-rush currents generated therein. For example, when charging capacitor banks the initial in-rush current causes very large transient current and voltage excursions. These transient voltages and currents can over-stress semiconductors and may damage other circuit components such as DC link capacitors and Electromagnetic Interference (EMI) filter components.

[0004] Fig. 1 illustrates a conventional soft-start circuit. Traditional soft-start circuits use a resistor 110 and a switching device 120 in the DC link 180 power pass that results in significant power dissipation. Additionally, the traditional soft-start design requires a high current rating of the controlled switching device 120 because the switching device 120 must accommodate the full current supplied to the back-end inverter 170 or other load. Further, an isolated power supply is required for triggering the soft-start supply because the switch is at the same high voltage as the DC link 180.

[0005] In the circuit of Fig. 1, the soft-start system interfaces between a front-end rectifier 160 and the back-end inverter 170. The front-end rectifier 160 receives AC power from a 3 phase AC power

source 150 and converts it into DC power. However, the DC power poses a problem if applied directly to the capacitor bank 130 because the capacitor bank appears as a short circuit when the DC voltage is first applied. Therefore, a current limiting resistor 110 is inserted into the circuit to limit the in-rush current when the DC voltage from front-end rectifier 160 is first applied. After the capacitor bank 130 is charged, the current draw from the capacitor bank essentially becomes zero. Additionally, the voltage across the DC bus 182, 184 approaches the output voltage of the front-end rectifier 160. The triggering circuit 140 detects this voltage and triggers the switching device 120 when the voltage reaches a predetermined threshold. Switching device 120 when activated shorts out resistor 110. However, as noted above, this disadvantageously place switching device 120 in series with the back-end inverter, which results in switching device 120 having to conduct the full current drawn by the back-end inverter. Thus, the switching device must be sized for this full current rating. Typically, the switching device120, heat sink (not shown) and related components will be relatively large and expensive.

[0006] Fig. 1 shows a conventional soft-start system that is used for preventing excessive current/voltage excursions during the initial starting of a power electronic system using a DC link. This design requires a high voltage and high current switching device with excessive power dissipation during normal operation. Alternatively, a relay can be used that is very expensive and bulky due to the high current and high voltage rating of the relay. Therefore, this soft-start system is difficult to implement and requires a large physical envelope for the components.

[0007] Therefore, it is desired to have a soft-start system that does not require the switching device, either solid state or electromechanical relay, to continuously carry the full current of the power system

SUMMARY OF THE INVENTION

[0008] In accordance with the present invention, the deficiencies in prior systems are overcome by providing a soft-start device for electrical power systems that has the switching device removed from the DC link power pass. According to the present invention, the switching device and resistor are placed in series with a capacitor bank out of the DC link power pass. According to an embodiment of the present invention, the soft-start system includes: a rectifier that receives AC power from a source and converts the AC power into DC power in a DC link; a capacitor connected to a first bus of said DC link; a resistor connected a second bus of said DC link, wherein said resistor and capacitor are connected in series; a switching device connected in parallel with said resistor; and a triggering circuit for measuring a DC voltage on the DC link and activating the switching device to short circuit the resistor.

[0009] According to another embodiment of the invention, a method for soft-starting a DC link in an electrical power system comprises: charging a capacitor connected to a first bus of the DC link, wherein a resistor is connected to a second bus of the DC link, and wherein the resistor and capacitor are connected in series; measuring the charge of the capacitor; and activating a switching device, wherein the switching device is connected in parallel with the resistor, and wherein the switching device when activated short circuits the resistor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] A more complete understanding of the present invention will become apparent from the following description taken in conjunction with the accompanying drawings, wherein:

FIG. 1 is a schematic illustration of a conventional soft-start system;

FIG. 2A is a schematic illustration of a soft-start system in accordance with one aspect of the invention;

FIG. 2B is an illustration of a hysteresis control of the switching device;

FIG. 3 is a schematic illustration of a soft-start system in accordance with another aspect of the invention; and

FIG. 4 is an illustration of test results of a soft-start system in accordance with the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0011] Aspects of the invention are disclosed in the accompanying description. Alternate embodiments may be devised without departing from the spirit or the scope of the invention.

[0012] FIG. 2A shows a soft-start system according to one embodiment of the present invention. The soft-start system for electrical power systems comprises a rectifier 260 that receives AC power from a source 250 and converts the AC power into DC power in a DC link 280. DC link 280 is used to supply a power device such as inverter 270. A capacitor 230 is connected to a first bus 282 of the DC link 280. A resistor 210 is connected a second bus 284 of the DC link 280. The resistor 210 and capacitor 230 are connected in series. A switching device 220 is connected in parallel with the resistor 210 and a triggering circuit 240 for measuring a DC voltage on the DC link 280 and activating the switching device 220 to short circuit the resistor 210.

[0013] Fig. 2B shows a hysteresis control for turn-on and turn-off of the soft-start switching device 220 shown in Fig. 2A. The horizontal axis shows DC bus voltage and the vertical shows status of the device. There are three zones, I, II, and III, that define the zones of operation. Zone I is the zone where the device is off (i.e., $Vdc < Vdc\_low$). Zone II is a transition zone and the device status depends on its previous state. For example, if the devices was off, it remains off until $Vdc > Vdc\_high$. Likewise, if the device was on, it remains on until $Vdc < Vdc\_low$. Finally, zone III is a zone where the device is on (i.e., $Vdc > Vdc\_high$). The triggering circuit can activate when the DC link voltage reaches a

predetermined threshold of Vdc_low volts, indicating the capacitor has been charged to a high enough voltage.

[0014] As shown in Fig. 2B, this means that as the capacitor is initially charging, the soft-start switching device remains off until Vdc exceeds the Vdc_high level. Once turned-on, the soft-start switching device remains on even though the DC voltage drops below Vdc_high. This is to prevent unnecessary turn-on/turn-off (i.e., chattering) of the switching device due to slight variations on the DC link voltage around this set point. However, if the DC bus voltage drops below Vdc_low, the switching device is opened and operation of the power electronics circuitry will be temporarily stopped until Vdc is increased to at least Vdc_high, when normal operation resumes by turning the soft-start switching device on and turning gating circuits on (e.g., on the active front-end rectifier or back-end inverter).

[0015] Those skilled in the art will appreciate that many alternative components and configurations can be used to achieve the above design. For example, the switching device 210 can be an Insulated Gate Bipolar Transistor (IGBT). However, any appropriate switching device, either electromechanical or solid state, can be used, such as a Bipolar Junction Transistor (BJT), Field Effect Transistor (FET), Metal Oxide Semiconductor FET (MOSFET), Silicon Controlled Rectifier (SCR), diode, hybrid device, and the like.

[0016] Further, those skilled in the art will appreciate that other combinations of devices can be added or altered without departing from the scope of the present invention. For example, a free wheeling diode 225 can be added to the switch device 220 or integrated into the switch device as part of a hybrid device. Other protection devices such as snubbers and the like could also be used as is well known in the art. The resistor 210 could be formed from several resistors, such as in a resistor bank. The resistor 210 can be made from any suitable material, such as metal, ceramic, carbon, semiconductor and combinations of these

materials, as is known in the art. Similarly, the capacitor can be in the form of a capacitor bank and likewise can be formed from any suitable material know in the art.

[0017] Still further, the switching device can be integrated with the rectifier, as shown in Fig. 3. This integration provides an even more compact and cost effective design. Since many of the elements of this design are the same as in the embodiment described in relation to Fig. 2, common elements will use the same reference number and not be further described.

[0018] Referring to Fig. 3, the rectifier can be formed of six co-packaged IGBTs as is well known in the art. Therefore, the rectifier configuration is not shown and will not be described further. The switching device 320 is a seventh IGBT. The rectifier and the switching device 320 can be contained in a single package 360. For example, the IGBTs of the rectifier and the switching device 320 can be contained in an Intelligent Power Module (IPM) 360, as shown. IPMs offer a low-cost integrated solution for power systems. The IPM 360 can comprise a three-phase IGBT bridge and IGBT switching device 320 along with the associated free wheeling diodes, such as diode 324, driving circuits for driving the IGBTs, a blocking diode 322 and external interface devices for coupling to the triggering circuit 240. The addition of all the necessary support and interface devices into one package along with the power IGBTs greatly reduces design and manufacturing cost and complexity. Additionally, the physical envelope required for the system is also reduced due to the integration of the components, which can be very advantageous especially for size restrictive environments such as electrical systems used in aerospace hardware. Those skilled in the art will appreciate that many other integrated combinations can be used. For example, the rectifier could be formed of a conventional diode bridge integrated with a switching device 320, such as an IGBT, SCR, MOSFET, and the like.

[0019] The triggering circuit 240 can encompass any variation of conventional triggering circuits, which are well known in the art. Further, the specific design of the triggering circuit will vary depending on the requirements of the switching device, as is also well known in the art. Therefore, the triggering circuit 240 will not be described in detail here. However, unlike conventional system, an isolated power supply is not required for the triggering circuit 240 because of the topology of the present invention. Therefore, the triggering circuit 240 can be supplied from the DC link 280 unlike traditional soft-start circuits, as shown in Fig. 1, which use a resistor and a switching device in the DC link power pass. The main limitation of Fig. 1 comes from the fact that the switching device 140 has the same high voltage potential as the DC link 180, and an isolated power supply is required for the triggering circuit 140 to activate the switching device 120.

[0020] In the above-described embodiments (i.e., Fig. 2A and Fig. 3) with an active rectifier front-end, a separate isolated power supply for the solid-state switching device is not needed. The present invention can use the same DC-DC power supply, which is providing power to the low side switching devices. This type of common power supply for low-side solid-state devices is well known in the art and will not be further discussed herein.

[0021] The operation of the previously described embodiments is similar. Initially, the capacitor 230 is charged through the series resistor 210. When the capacitor 230 is charged to a predetermined high voltage (i.e., Vdc_high) potential, the resistor 210 is shorted-out through a control signal sent to the switching device 220. As previously noted, this implementation is simple, cost effective, and accommodates the utilization of the 7th IGBT of a 7-pack IPM. Additionally, this approach significantly reduces the power dissipation of the soft-start switching device during normal operation and provides a lightweight, low cost and reliable soft-start circuit for any DC link capacitor.

[0022] According to another embodiment of the invention, a method for soft-starting a capacitor in a DC link in an electrical power system is provided. The method includes charging a capacitor connected to a first bus of the DC link, wherein a resistor is connected to a second bus of the DC link and the resistor and capacitor are connected in series. The charge of the charge of the capacitor is then measured. A switching device is then activated. The switching device is connected in parallel with the resistor and when activated short-circuits the resistor.

[0023] Those skilled in the art will appreciate that many variations can be made to the above steps without departing from the scope of the invention. For example, the charge on the capacitor can be measured by measuring current flow into the capacitor. Alternatively, the charge on the capacitor can be measured by measuring voltage across the resistor (i.e., the capacitor is charged when the resistor voltage approaches zero), current through the resistor, or voltage across the capacitor. Still further, the charge of the capacitor can be measured by a timing circuit that has an appropriate delay to allow for the capacitor to charge.

[0024] However, the preferred control method for the switching device would be voltage control of the DC link with built-in hysteresis to prevent nuisance turn-on/turn-off of the switching device due to variations in the DC bus voltage around Vdc-high set-point as described in detail in Fig. 2B.

[0025] The present invention significantly reduces power dissipation of the soft-start switching device because it is placed in the DC link capacitor path that only sees the harmonic currents during normal operation. Therefore, the switching device needs only to be rated to accommodate the harmonic current and not the full system current as in the conventional design. Consequently, the cost of the switching device according to the present invention is much less than for similar conventional designs.

[0026] Fig. 4 shows test results obtained from a system according to the present invention. Four typical soft-start waveforms are illustrated for a motor controller powered by a circuit as shown in Fig 2A. Trace 1 illustrates the AC input voltage for Phase A, line to neutral. Trace 2 illustrates the AC source "phase A" current (i.e., the input current to the front-end rectifier). Trace 3 illustrates the DC link voltage and trace 4 illustrates the DC link capacitor current. As can be seen from these waveforms, the source-side input voltage and current do not present any soft-start related transients, due to the above-described soft-start circuit. The input line current is limited to less than one per unit and DC link current during initial start is controlled to a safe current, that does not significantly exceed normal operating currents.

[0027] The foregoing illustrates the principles of the invention. It will be appreciated by those skilled in the art will that various arrangements of the present invention can be designed. For example, the trigging circuit could also be integrated with the rectifier and switching device in a custom Application Specific Integrated Circuit (ASIC), as the triggering circuit does not need an isolated supply. Additionally, the soft-start system has been shown in connection with an inverter. However, those skilled in the art will appreciate that the present invention can be used to supply DC power to any suitable device. Therefore, the scope of the invention is not limited by the foregoing description but is defined solely by the appended claims.